D-wave Symmetry Confirmed in High T_c Superconductors

Imaging of Electronic States at Impurity Atoms Reveals D-wave Symmetry

A research team led by J.C. Seamus Davis of the Materials Sciences Division has provided important new insights into high-temperature superconductivity. In a paper published in *Nature* and discussed in a cover story in *Physics Today*, they reported their new evidence of the "d-wave" nature of the "superconducting pairs" in these materials.

The mechanism of superconductivity in cuprate-based high-T_c superconductors has been the subject of intense investigation since their discovery in 1986. Despite this effort, much remains unknown. When a superconductor (high-T_c or normal) is cooled below its T_c, some of its electrons "associate" to form "Cooper pairs;" pairs of electrons that can travel through the materials without electrical resistance. These electrons could pair in several possible configurations: including a symmetric "s-wave" state with zero angular momentum or an anisotropic "d-wave" state with two units of angular momentum. The currently accepted model of high-T_c superconductivity predicts d-wave symmetry for the Cooper pairs. Despite its critical importance to the validity of the theory, this prediction has proven quite difficult to verify experimentally.

In 1993, workers at University of California at Santa Barbara predicted that properly placed impurity atoms might perturb the electronic states in their vicinity just enough to reveal the underlying symmetry of the superconducting pairs. However, the predicted perturbations were small and beyond the sensitivity of experimental capabilities of the time. To address this challenge, the Berkeley team built a highly sensitive, cryogenic Scanning Tunneling Microscope (STM) designed specifically for studies of high-T_c materials. They then carefully doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) with Zn atoms which were expected to create a relatively large perturbation. It is well-known that the electronic states that are involved in superconductivity in high-T_c materials do not constitute a continuous energy spectrum but instead, manifest a characteristic "energy gap;" that is, in a certain range of energies there are no states available. As a consequence, in the superconducting state, there is a finite energy required to produce an electronic transition (this energy is the magnitude of the energy gap). The Berkeley STM was designed to study spatial variations of electronic quantum states generated within this energy gap by impurity atoms. If the superconductivity were s-wave-like, theory predicts that these states, as made observable by the impurity (impurity state), would be similar in all directions in the CuO_2 planes (isotropic). However, if superconductivity were d-wave like, the impurity-state should be anisotropic, with a characteristic lobed shape, largest along the direction of the Cu-O bonds and zero along the diagonals of the square CuO_2 lattice (see figure). When the surface of freshly cleaved BSSCO was imaged in a "differential scanning" mode designed to reveal local variations of electron density, numerous bright spots were found where the Zn atoms perturbed the superconducting state. With atomic resolution, these impurity states had the predicted distinctive lobed pattern corresponding to d-wave symmetry (see figure).

The Berkeley work provides the first atomic-scale proof of the d-wave symmetry of the Cooper pairs in high-T_c materials, and hence of the current model of high-T_c superconductivity. More generally, the work demonstrates the promise of using atomic-scale imaging of impurities to reveal otherwise unobservable electronic phenomenon in solids. Interestingly, in the BSCCO work, the team also observed some weak structures in the electronic states that had not been predicted by theory. These observations illustrate both the power of the technique and the need for new and more sophisticated models to explain the physics of high-T_c superconductivity at the atomic scale.

J.C. Seamus Davis, (510) 642-4505, http://socrates.berkeley.edu/~davisgrp/; Materials Sciences Division (510 486-4755), E. O. Lawrence Berkeley National Laboratory.

S. H. Pan, E. W. Hudson, K. M. Lang, H. Eisaki, S. Uchida, and J. C. Davis, "Imaging the effects of individual zinc impurity atoms on superconductivity in $Bi_2Sr_2CaCu_2O_{8+\delta}$," *Nature* **403**, 746 (2000).

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